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Landslide hazard and risk zonation—why is it still so difficult?

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Abstract The quantification of risk has gained importance in many disciplines, including landslide studies. The literature on landslide risk assessment illustrates the developments which have taken place in the last decade and that quantitative risk assessment is feasible for geotechnical engineering on a site investigation scale and the evaluation of linear features (e.g., pipelines, roads). However, the generation of quantitative risk zonation maps for regulatory and development planning by local authorities still seems a step too far, especially at medium scales (1:10,000–1:50,000). This paper reviews the problem of attempting to quantify landslide risk over larger areas, discussing a number of difficulties related to the generation of landslide inventory maps including information on date, type and volume of the landslide, the determination of its spatial and temporal probability, the modelling of runout and the assessment of landslide vulnerability. An overview of recent developments in the different approaches to landslide hazard and risk zonation at medium scales is given. The paper concludes with a number of new advances and challenges for the future, such as the use of very detailed topographic data, the generation of event-based landslide inventory maps, the use of these maps in spatial-temporal probabilistic modelling and the use of land use and climatic change scenarios in deterministic modelling.

Keywords Landslide risk · Risk zonation · Probabilistic modelling · Deterministic modelling

Résumé La quantification des risques a pris de l’importance dans beaucoup de disciplines, y compris dans les études de glissements de terrain. La documentation sur l’évaluation des risques de glissement illustre les développements réalisés durant les derniers dix ans, montrant l’apport de ces approches dans les reconnaissances géologiques de sites et les études de tracés linéaires (e.g., pipelines, routes). Cependant la production de cartes de zonage des risques pour l’aménagement du territoire pour les besoins des autorités locales semble encore un objectif lointain, spécialement pour les échelles intermédiaires (1/10000 à 1/50000). Cet article fait le point sur les essais de quantification des risques de glissements de terrain sur de grandes régions, présentant les différentes difficultés relatives aux inventaires de glissements incluant des données sur la date, le type et le volume du glissement, la détermination des probabilités d’occurrence spatiale et temporelle, la modélisation des propagations de débris et l’évaluation des vulnérabilités. Une vue d’ensemble est présentée concernant les différentes approches du zonage des risques de glissements de terrain aux échelles moyennes. L'article conclut avec diverses avancées récentes et défis pour le futur, tels que l'utilisation de cartes topographiques très détaillées, la production de cartes d'inventaires de glissements, l'utilisation de ce type de cartes dans les modélisations probabilistes et la prise en compte de scénarios relatifs à l'aménagement du territoire et aux changements climatiques dans les modélisations déterministes.

Mots clés Risque de glissement de terrain · Zonage de risque · Modélisation probabiliste · Modélisation déterministe

What is landslide risk?

One of the most useful definitions of risk is presented by Varnes (1984) as "the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period". When dealing with physical losses, (specific) risk can be quantified as the product of vulnerability, cost or amount of the elements at risk and the probability of occurrence of the event with a given magnitude/intensity.

When we look at the total risk, the hazard is multiplied with the expected losses for all different types of elements at risk (= vulnerability × amount), and this is done for all landslide types. Schematically, this can be represented by the following formula, based on Varnes (1984), Fell (1994), Leroi (1996) and Lee and Jones (2004):

$$\text{Risk} = \sum \left(H \sum (VA) \right) \tag{1}$$

where:

H	Hazard expressed as probability of occurrence within a reference period (e.g., year, design period of a building). Hazard is a function of the *spatial probability* (related to static environmental factors such as slope, strength of materials, depth, etc.) and the *temporal probability*, related indirectly to some static environmental factors like slope and hydraulic conductivity and directly to dynamic factors like rain input and drainage
V	Physical vulnerability of a particular type of element at risk (from 0 to 1) for a specific type of hazard and for a specific element at risk
A	Amount or cost of the particular elements at risk (e.g., number of buildings, cost of buildings, number of people, etc.)

The calculation of the consequences (VA) has to be done for all elements at risk, and the results added for one particular landslide hazard (the probability for a specific combination of landslide type and magnitude). The specific risk would result in a single value of potential losses for a given probability. Theoretically, the formula would result in a so-called risk curve, containing the relation between all events with different probabilities, and the corresponding losses, which forms the basis for the phases of risk reduction, risk transfer and preparedness planning (Lee and Jones 2004).

The risk formula looks deceptively simple, but when one tries to work it out for a particular situation, such as for the specific risk to buildings or persons in buildings (see Fig. 1) the formula quickly turns out to be very complicated and a lot of aspects should be taken into account which are difficult to evaluate. Figure 1 is a typical site investigation situation in great detail to highlight the complexity of the system.

When we want to upscale the example illustrated in Fig. 1 to a map and carry out a risk zonation for larger areas, it is very difficult to locate exactly the element at risk versus the possible locations of the landslides. The use of the formula requires the analysis of the spatial and temporal probabilities that groups of elements at risk in the map are hit by mass movements of different particular magnitudes, which are then used to estimate the degree of loss.

A schematic overview of the procedure for a GIS-based landslide risk assessment at a large or medium mapping scale (e.g., 1:10,000–50,000) is given in Fig. 2. The top of the flowchart displays the four basic types of input data required: environmental factors, triggering factors, historic landslide occurrences and elements at risk.

Of these types of input data, the historic information on landslide occurrences is by far the most important, as it gives insight into the frequency of the phenomena, the types involved, the volumes and the damage that has been caused. Landslide inventory maps, derived from historic archives, field data collection, interviews and image interpretation are essential but unfortunately often lacking which makes a quantitative risk assessment very difficult.

Information on triggering factors consists of earthquake and rainfall records, which have to be converted into magnitude–frequency relations of those aspects that actually trigger landslides, e.g., earthquake acceleration or groundwater depth. These parameters are very site specific and can only be modelled properly using deterministic (geotechnical or hydrological) models, which require considerable input on the geotechnical characterization of the terrain (soil depth, cohesion, friction angle, permeability).

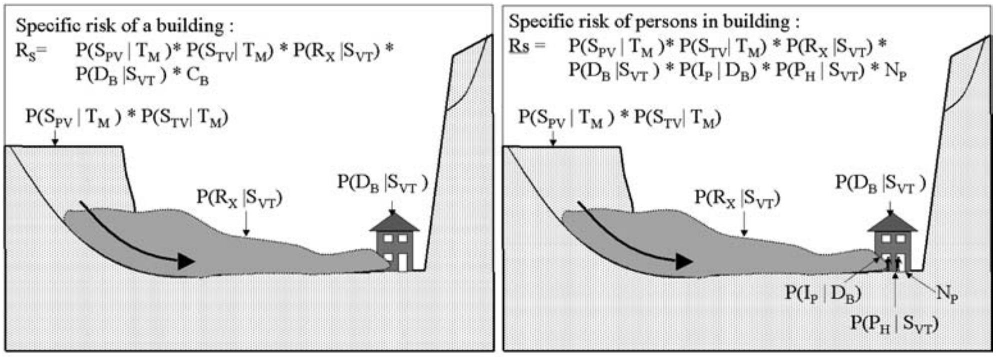


Fig. 1 Example of possible calculation methods for specific risk to buildings and persons in buildings

In which:

$P(S_{PV} \mid T_M)$= Spatial probability. Conditional probability of initiating a landslide with a specific volume and type at a specific location, given a certain triggering event (e.g. rainfall, earthquake) with a certain magnitude/intensity.

$P(S_{VT} \mid T_M)$ = Temporal probability. Conditional probability of initiating a landslide with a specific volume and type , given a certain triggering event (e.g. rainfall, earthquake) with a certain magnitude/intensity, within a certain time period.

$P(R_X \mid S_{VT})$ = Conditional probability that a runout zone with distance X to the building will be covered, given the occurrence of the landslide with a particular volume and type.

$P(D_B \mid S_{VT})$ = Conditional probability of damage to the building of a particular construction type, given the occurrence of the landslide with a particular volume and type.

C_B = replacement costs of the particular building.

$P(I_P \mid D_B)$ = Conditional probability of injuries or death for a person present in the house, given the degree of damage to the building by a landslide of a given volume and type

$P(P_H \mid S_{VT})$ = Conditional probability of persons being present in the building, given then time of the day that the landslide might occur (or percentage of persons in the building given time of the day)

N_P = Number of persons in the building

Determining temporal probability is done either by correlating the data on landslide occurrences with those of the triggering factors (provided that the historical records are sufficient for this) or through dynamic modelling (Van Beek 2002).

The spatial probability can be obtained either through dynamic modelling or through analysing the relation between the locations of past landslide events and a set of environmental factors, in order to predict areas of landslide initiation that have similar combinations of factors, using heuristic or statistical methods. The spatial information on landslide initiation locations is used in combination with the environmental factors, of which the Digital Elevation Model (DEM) is the most crucial one, in the modelling of the runout distance for landslides of a particular type and volume. The

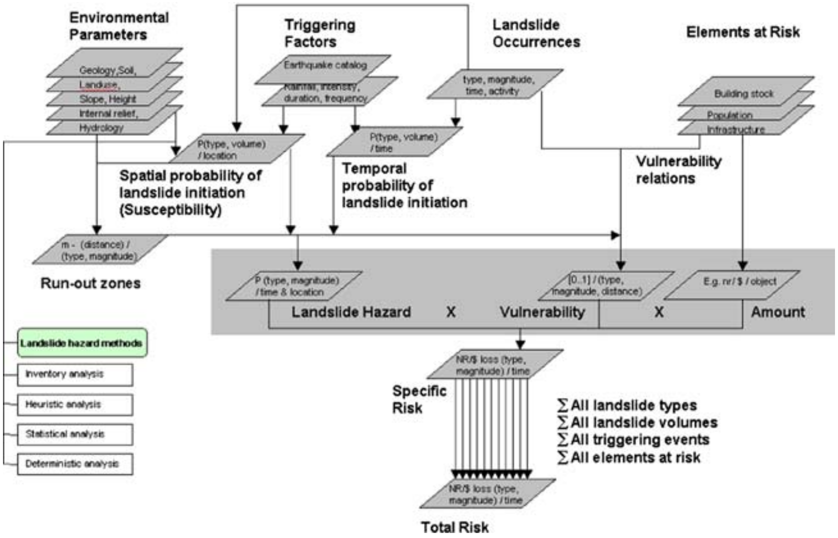


Fig. 2 Schematic representation of spatial landslide risk assessment methodology

combination of landslide initiation zones, with temporal and spatial probability, and runout zones results in a landslide hazard map.

However, most hazard maps are still of a qualitative nature and concentrate basically on determining the susceptibility, which can be seen as a relative indication of the spatial probability. Determining temporal probability is often not possible, due to the absence of historical landslide records that effectively can be related with the historical records of the most important triggering events (rainfall and earthquakes), scarcity of input data, or the absence or insufficient length of historical records of the triggering events.

One of the other main types of data for landslide risk assessment is the elements at risk. Elements at risk refer to the population, buildings, civil engineering works, economic activities, public services, utilities and infrastructure, etc., which are at risk in a given area. Emphasis is mostly given to buildings, population and infrastructure. Data collection techniques for a rapid inventory of elements at risk generally use high-resolution images and result in the generation of multipurpose elements at risk databases. Each of the elements at risk has its own characteristics, which can be spatial (the location in relation to the hazard), temporal (such as the population, which will differ in time at a certain location) and thematic characteristics (such as the material type of the buildings or the age distribution of the population).

The next step in the analysis of risk is the quantification of the vulnerability of the elements at risk, which is achieved by making an assessment of the degree of damage that may result from the occurrence of a landslide of a given type and volume. The estimation of the possible degree of damage should be based on damage relations, also called vulnerability/fragility curves derived from historical damage inventories. They can also be derived from detailed structural modelling or through empirical relations.

The last component of the flowchart is the combination of hazard and vulnerability information to give values of specific risk. The quantification of the amount to be included for the elements at risk could be in terms of monetary values (although this is often not required) or in the number of buildings or persons affected. The combination of the data for one specific type of landslide and one specific type of elements at risk results in a specific risk. The integration of all specific risks for all landslide types and volumes and all elements at risk results theoretically in the total risk.

The flowchart in Fig. 2 is a theoretical one; a very few published works on landslide risk assessment actually calculate total risk. The ones that do are nearly all related to site investigations, or very small areas. Very limited work on quantitative landslide risk assessment has been carried out with larger areas as the basis for zonation.

What makes it so difficult to map landslide risk?

In order to improve the results of landslide risk assessment, it is necessary to evaluate the whole process as represented in Fig. 2 and determine the difficulties in every step. The result will give the starting point for an analysis of how more satisfactory results in risk assessment may be obtained. Figure 3 illustrates some of the difficulties involved in calculating landslide risk.

Figure 3 shows a schematic representation of two buildings (elements at risk) which present different vulnerabilities as they are geographically located in diverse positions and might be affected by different types of landslides and in different ways (undercutting/impact). Vulnerability is also determined by construction type (e.g., building materials, foundation types), which determines the capacity of the building to withstand impact/erosion. In addition, due to their use, structure and size, the value or cost of these buildings will also be different. In the calculation, therefore, each building will have a different value and for the same hazard (e.g., a 10 years return period landslide) the risk will be also different. Furthermore, when calculating the risk to persons, temporal changes in vulnerability also play a major role, both for persons in the buildings and in risky locations outside (e.g., in traffic).

Although the determination of the temporal vulnerability of the elements at risk might be problematic and the process quite time consuming, the elements at risk themselves can be mapped and classified without many conceptual problems.

Of the three risk determining factors indicated in Eq. 1, the hazard component is by far the most complex to establish. Figure 3 illustrates several of the problems associated with determining the temporal and spatial probability of occurrence, the volume of the expected

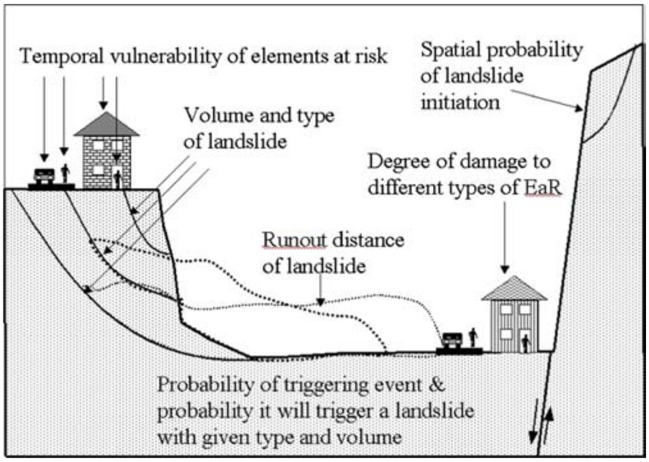


Fig. 3 Illustration of some of the most problematic aspects of landslide risk assessment

landslide and the limits to which the landslide might move (runout zone).

Difficulties related to landslide inventory mapping

Landslides are generally isolated processes which individually may not be very large in size but which can occur with a high frequency in a region. Unlike hazardous events that affect large areas, such as earthquakes or flooding, the generation of landslide inventory maps and databases is a tedious procedure. Landslides have to be mapped and described one by one, and each one might have different characteristics. In most countries there is no single agency that has the responsibility for maintaining a landslide database. At best, several organizations, such as the public works department or road department, will deal only with those landslides that have affected their area of interest (e.g., road network), resulting in incomplete and biased databases. Newspaper and other historical records only record those events that caused substantial damage. Universities and research institutes do work on landslide inventory maps but mostly as part of a research project, with a limited duration, after which a landslide database is no longer kept up-to-date. Therefore, it is very difficult to obtain landslide inventory maps that are complete, both with respect to the area covered and to the time period investigated (Ibsen and Brunsden 1996). Even when such a map exists, it seldom gives adequate information on the type and characteristics of the slope failure. One way to overcome this problem is to complement the historic information with landslide interpretations from aerial photographs or satellite images. This would allow landslide inventory maps for fixed periods, related to the available imagery. However, for most of the mapped landslides the exact date of occurrence remains unknown, thus making it difficult to correlate the landslide with a triggering event, especially as different landslide types have different meteorological triggers. This lack of landslide inventory maps also leads to problems in the development of vulnerability relations and in validating landslide hazard maps.

Difficulties related to the assessment of spatial probability

In order to obtain quantitative risk maps, the first essential requirement is to carry out a quantitative hazard assessment. Most hazard maps are still of a qualitative nature and concentrate basically on determining the susceptibility, which can be seen as a relative indication of the spatial probability. The spatial probability or landslide susceptibility can be obtained using different analytical approaches.

Statistical landslide hazard assessment has become very popular, especially with the use of Geographic Information Systems (GIS) and the possibility of applying data integration techniques that have been developed in other disciplines. This requires a landslide inventory map which is used in combination with a series of environmental factors, and is based on the assumption that landslides are likely to occur under the same conditions as those under which they occurred in the recent past. However, the terrain conditions change after the occurrence of a landslide and therefore many of the environmental factors, such as slope angle or land use, are different after the occurrence of the landslide. Furthermore, the specific combination of environmental factors is quite different for different landslide types, landslide depths and landslide volumes.

Very few studies develop separate statistical models for different landslide types and most merge all active landslides together in one group which is used to generate statistical relations. Statistical landslide susceptibility assessment hardly ever takes the triggering factors into account, and if this is done, it is mostly the spatial variation of the factor (e.g., rainfall amount, seismic acceleration) and not the temporal aspect. In landslide susceptibility assessment, the use of expert opinion is more and more considered as "subjective" and sought to be replaced by "objective" computer algorithms. GIS-based statistical landslide susceptibility assessment is often more focused on the tool than on the input data and frequently involves an extreme simplification of the landslide controlling factors.

On the other hand, deterministic modelling might give more reliable answers but requires detailed datasets about the spatial variation of parametric values which form the input of the hydrological and slope stability models. The most sensitive parameters are slope values (which can easily be obtained from accurate DTM nowadays) and soil thickness. The spatial distribution of this parameter is extremely difficult to measure. If the soil thickness is unknown, then the ratio between the height of the phreatic surface and the soil thickness is also unknown. This ratio is a sensitive parameter for the stability of slopes. Although geomorphological models give a certain prediction for soil depth, its spatial variability is large. The weathering processes in the underlying rocks are a factor that is often neglected. Material properties (c and ϕ) are difficult to measure for many points over large areas and show a high spatial variability. In a GIS environment only the infinite slope stability model with the slip plane parallel to the surface can be used efficiently for larger areas, as landslide models on the catchment scale, with complex or curved slip surfaces, are difficult to implement.

Difficulties related to the analysis of temporal probability

Landslides are localized processes, which normally do not happen with different frequency and magnitude at the same location. Debris flows and rockfall occurrences may be the exception to this rule. But for most types of landslides, once the movement has occurred, the slope conditions are changed and a repetition of a similar event in the same location is not likely to happen. In other words, unlike earthquakes, floods or debris flows and snow avalanches with fixed runout tracks, landslides do not normally have a magnitude–frequency relation for a given location. However, it is possible to elaborate frequency–magnitude relationships for landslide occurrences over a larger area, such as an entire watershed, by mapping the landslides taking place due to particular triggering events and relate the spatial frequency to the return period.

The absence or incompleteness of landslide records is one of the major drawbacks in the assessment of landslide hazard risk. For this reason it has been impossible in most parts of the world to establish the quantitative relationship of the occurrence of landslides with important triggering factors, such as earthquakes and rainfall, of which magnitude–frequency functions are known.

Difficulties related to landslide runout modelling

Landslide runout modelling for the many possible landslide initiation areas in a given locality remains very difficult. It can be done on the basis of former incidents to construct maximum friction lines, which determine the runout distance, or variable friction lines in relation to environmental factors, in order to create a GIS zonation of impact probabilities. However, such empirical analyses require a lot of data. Abundant datasets exist for snow avalanches but in most cases not for landslides. In the deterministic approach the parameterization of the runout models is very difficult because measurements of material properties cannot be done during rapid flows. Moreover routing of material on slopes without predefined tracks, for example, on debris fans or cones, requires very detailed DTMs and several technical problems are encountered when modelling the propagation in a GIS environment.

Difficulties related to landslide vulnerability assessment

The vulnerability of elements at risk related to landsliding is extremely difficult to establish for most landslide types (debris flows and rockfalls may be exceptions). This is due to the fact that very limited damage data are available, with the exception of particular areas such as Hong Kong. Furthermore, the magnitude of a possible slide is difficult to foresee as it depends on the magnitude of the triggering event and the environmental conditions (e.g., height of water table) at the moment of the event. Table 1 gives a schematic overview of different types of damage that might be caused by different landslide types and different elements at risk.

Unlike other hazards (earthquakes, floods, windstorms) loss estimation models do not exist for landslide hazard. Again, the explanation lies in the first place in the scarcity of historic data. Furthermore the damage due to landslides is more isolated (damage in "points") than for other events, which may cause damage in "polygons" (e.g., earthquakes, floods). The scarcity of such vulnerability information for different landslide types, volumes and elements at risk might well be one of the largest obstacles in landslide risk assessment.

Landslide risk approaches used

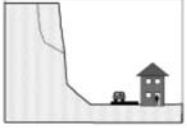
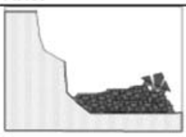
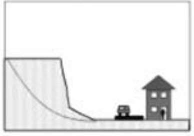
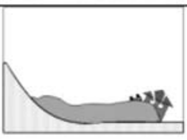
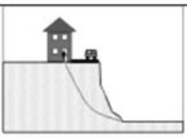
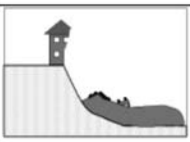
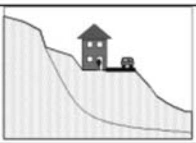
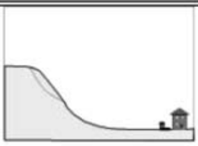
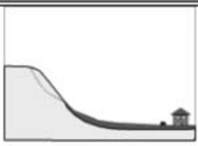
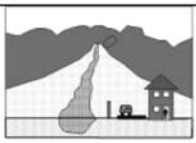
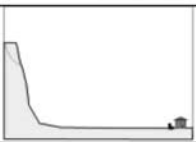
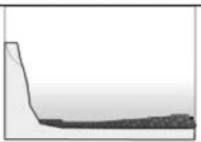
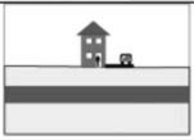
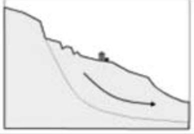
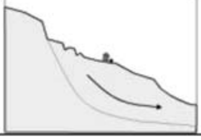
Overviews and classification of GIS-based landslide hazard assessment methods can be found in Soeters and Van Westen (1996), Carrara et al. (1995, 1999), Guzzetti et al. (1999) Aleotti and Chowdury (1999) and Van Westen (2000). There is a general consensus that a classification may involve four different approaches:

- Landslide inventory-based probabilistic approach
- Heuristic approach (direct—geomorphological mapping or indirect—combination of qualitative maps)
- Statistical approach (bivariate or multivariate statistics), and
- Deterministic approach (Soeters and Van Westen 1996).

The number of publications on landslide risk assessment is still rather modest, but recently some good overview publications on landslide risk methods have been published (e.g., Cruden and Fell 1997; Guzzetti 2000; Dai et al. 2002) including a recent textbook by Lee and Jones (2004). The classification of the published landslide risk assessment methods is still not very detailed but that proposed by the Sub-committee on Landslide Risk Management of the Australian Geomechanics Society has been generally adopted. This classification is based on the level of quantification dividing the landslide risk assessment methods into:

- Qualitative methods (probability and losses expressed in qualitative terms)
- Semi-quantitative methods (indicative probability, qualitative terms), and
- Quantitative methods (probability and losses quantified)

Table 1 Schematic overview of landslide damage types, related to different types of landslides, elements at risk and the location of the elements at risk in relation to the landslide

Type	Before	After	Likely damage to elements at risk	Factors determining risk
Impact by large rockmass			**Buildings:** Total collapse likely **Persons in buildings:** Loss of life/ major injury likely **Infrastructure:** Coverage and obstruction / destruction of surface **Persons in traffic:** Loss of life/ major injury possible	- Volume of rockfall mass - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Intermediate obstacles - Precursory events
Impact by single blocks			**Buildings:** Total collapse not likely. Localized damage **Persons in buildings:** Minor to major injury likely **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** Loss of life/ major injury possible	- Volume of rockfall blocks - Number of rockfall blocks - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Intermediate obstacles
Impact by landslide mass			**Buildings:** Collapse / major damage depending on volume **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** None, persons are normally able to escape	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Distance to Elements at risk - Local topography along track - Speed of landslide movement
Loss of support due to undercutting			**Buildings:** Collapse / major damage likely **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Complete destruction of road surface. **Persons in traffic:** None, persons are normally able to escape	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Retrogressive landslide - Cliff erosion - Speed of landslide movement
Differential settlement /tilting due to slow movement			**Buildings:** Tilted buildings with cracks. Normally no collapse **Persons in buildings:** None, slow movement. People not in danger **Infrastructure:** Tilting and cracks, traffic slowed down **Persons in traffic:** None, slow movement	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Speed of landslide movement - Amount of displacement
Impact by debris flow on slope			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** Minor-major injuries. Depends on speed. **Infrastructure:** Coverage of road surface. Obstruction of traffic. **Persons in traffic:** Minor-major injuries. Depends on speed.	- Volume of landslide mass - Water content - Slope steepness - Local topography - Landslide material type - Triggering factors - Speed of movement - Size of blocks transported
Flooding by debris flow on alluvial fan			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage **Persons in traffic:** None, persons are normally able to escape	- Volume of debris flow - Water & sediment content - Local topography of fan - Triggering factors - Distance from source - Distance from lahar channel - Speed
Impact by Sturzstrom			**Buildings:** Total collapse **Persons in buildings:** Loss of life **Infrastructure:** Total destruction **Persons in traffic:** Loss of life	- Volume of rockfall mass - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Distance from source zone - Precursory events
Liquefaction			**Buildings:** Differential settlement, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks **Persons in traffic:** no-injuries	- Soil types - Soil strength - Grainsize distribution - Foundation types - Earthquake intensity - Water table
Deep seated creep movement			**Buildings:** Differential settlement, tilting, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks, broken pipes **Persons in traffic:** no-injuries	- Speed of movement - Local geological situation - Age of landslide - Seasonality of movement

If the methods described for landslide risk assessment are combined with the methods reported for calculating the hazard component, the value of a number of combinations is more obvious. Table 2 gives an indication of the usefulness of particular hazard approaches for the three types of landslide risk assessment methods, given that they are carried out over relatively large areas at medium scales (1:10,000 – 1:50,000) using GIS-based methods for risk zonation.

The numbers in Table 2 have the following explanation:

- 0 : The hazard method is not appropriate for the risk method.
- 1: Moderately useful combination. The hazard method is less appropriate for the risk method.
- 2: Highly useful combination. The hazard method could be the best method for risk assessment, but this depends on the availability of data (e.g., historical landslide records)
- 3: Most useful combination, which will result in the best risk assessment given the available input data.

For quantitative risk assessment, landslide inventory-based probabilistic methods are generally the best methods, assuming that the occurrence of landslide events in the past is a good indication of the likelihood of the phenomena occurring in the future. However, the method requires fairly complete historical landslide records and may be less useful for the risk assessment in areas that have had large environmental changes in the past or where, as a consequence of climate change, the landslide frequency is expected to change significantly.

Generally speaking, the best option for quantitative landslide risk assessment is the application of deterministic slope stability models, combined with dynamic models for hillslope hydrology. These may provide scenarios of potential instability under varying environmental and climatic conditions (Van Beek 2002), but are very data demanding over larger areas and require a substantial degree of simplification of the landslide types and depths.

Table 2 Usefulness of specific combinations of hazard approaches and risk approaches for GIS-based landslide risk zonation at medium scales

	Risk approaches		
	Qualitative	Semi-quantitative	Quantitative
Hazard approaches			
Inventory-based probabilistic approach	2	2	2
Heuristic/ geomorphological/ direct mapping/ expert-based approach	3	3	0
Statistical approach (bivariate or multivariate)	3	2	2
Deterministic and dynamic modelling approach	0	1	3

The combinations are indicated with a number from 0 (not useful) to 3 (most useful). See text for explanations

Statistical hazard methods are good for assessing the spatial probability but there are problems in evaluating either temporal probability or the effects of future environmental changes. They are mostly used in qualitative risk assessment but if combined with landslide inventory maps for different triggering events, might be the best method for quantitative risk assessment over larger areas.

Heuristic approaches are suitable for qualitative and semi-quantitative risk assessment and can provide reliable maps over larger areas with limited costs, provided they are carried out by (teams of) experts.

The following sections give an inventory of recent developments in each of the four above-mentioned hazard approaches (Table 2)

Developments in the use of landslide inventory methods for landslide risk assessment

There are few places in the world that have fairly complete historical landslide records for the past 50–100 years. National landslide inventory databases have been developed in several countries, and are sometimes accessible through the Internet (Dikau et al. 1996). Among the best examples are those from Italy (Guzzetti 2000; Guzzetti and Tonelli 2004), Hong Kong (Ho 2004), Switzerland (Lateltin 1997), France (Faure et al. 1988), Canada and Colombia (Gonzalez 1989). If such records are available they can be used as the main input in probabilistic landslide hazard assessment, which forms the basis for quantitative risk assessment. According to Crovelli (2000) two general types of probability models are applicable for landslide hazard assessment using historical landslide data: continuous time-based models and discrete time-based models in which time is partitioned in a series of time increments within which a landslide may or may not occur. For example, Coe et al. (2004a, b), present work using a landslide database for the city of Seattle for the period 1909–1999. They were used as input to the Poisson model, which estimates the probability of the future occurrence of individual landslides, and the binomial probability model, which estimate the probability of having a group of landslides within an individual year. The resulting maps display landslide density, mean recurrence intervals and exceedance probabilities.

Hong Kong is another example of an area with an extensive historical landslide database which has been used to estimate the annual probability of failure for cut-slopes, using a combination of a probabilistic method and a heuristic adjustment factor (Finlay et al. 1997). Historical landslide records have also been used for the calculation of probability of landslide-triggering events, such as rainfall or seismic activity. A famous area where conditions are favourable for this type of analysis is New Zealand, where rainfall thresholds have been defined and for each of these rainfall classes, the landslide probabilities have been determined (Glade 1997; Crozier and Glade 1999). It is considered essential to estimate frequency and magnitude of future events and it should be advocated that directly after any major disaster event (earthquake, rainstorm, hurricane, etc.), an inventory of the landslide phenomena and the degree of damage to different elements at risk be made by geomorphologists.

Developments in the use of heuristic methods for landslide risk assessment

In many countries qualitative risk assessment procedures based on heuristic approaches have been implemented, for example, in California (Blake et al. 2002), New Zealand (Glassey et al. 2003), Australia (AGSO 2001; Michael-Leiba et al. 2003), France (Flageollet 1989) or Switzerland (Lateltin 1997). For example, in Australia, the National Geohazards Vulnerability of Urban Communities Project (or Cities project) was a programme to analyse and assess the risks posed by a range of geohazards, including landslides, to urban communities, mostly following expert-based or geomorphological methods (AGSO 2001). The quantification of landslide risk is often a difficult task for large areas, as both the landslide intensity and frequency will be difficult to calculate for an entire area, even with sophisticated methods in GIS. In practice, simplified qualitative procedures are often used, such as that developed in Switzerland (Lateltin 1997) (See Fig. 4).

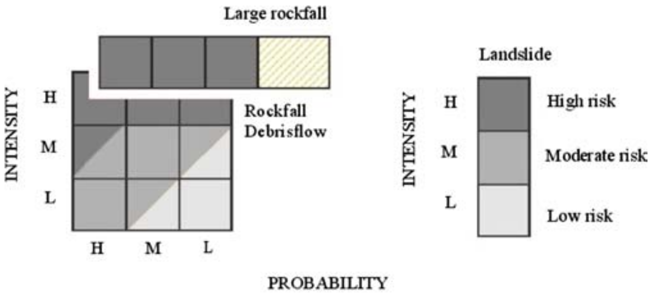
The qualitative approach is based on the experience of experts, with the risk areas categorized as "very high", "high", "moderate", "low" and "very low" risk. It is recommended that these levels of risk include a description of their practical implications (e.g., in very high risk areas: "immediate physical and non-physical remedial measures are required and no more infrastructure development must be allowed in this area"). A guideline for terminology for assessing risk to property was developed by the Australian Geomechanics Society and the Sub-committee on Landslide Risk Management (AGS 2000) considering a combination of landslide likelihood and the possible consequences (similar to the method shown in Fig. 4). This method is applicable for spatial analysis using GIS.

The increasing popularity of GIS over the last decades has led to a majority of studies using indirect susceptibility mapping approaches (Aleotti and Chowdury 1999). As a consequence there are less publications in which GIS is used in combination with a heuristic approach, either geomorphological mapping or index overlay mapping (e.g., Barredo et al. 2000; Van Westen et al. 2000). Data collection by experts remains necessary as existing databases have proved to be insufficient and data in accessible files contain too much inconsistent data. Furthermore, the list of difficulties related to susceptibility, hazard and frequency assessments clearly indicates that a large amount of input by the expert is still required to improve hazard and subsequent risk zonation. In relation to the hazard zonation, it has to be observed that the use of expert models based on the combination of heuristic reasoning by the geomorphologist and computer-assisted modelling gives the best results. An example from the US is the SMORPH model which classifies hillslopes as either high, moderate or low landslide hazard, based on their local topographic slope and curvature.

Risk mapping would profit considerably from a pragmatic-oriented approach, e.g., selecting only those types of slope failures that are known to have caused damages in the area under consideration in the past and to consider the risk determining factors as mentioned in Table 1.

Developments in the use of statistical methods for landslide risk assessment

Geographic Information Systems are very suitable for indirect landslide susceptibility mapping, in which all



	Intensity classes		
	Low intensity	**Moderate**	**High**
Rockfall	E <30 KJ	E: 30 – 300 KJ	E < 300 KJ
Massive rockfall	-	-	E > 300 KJ
Sliding	V <= 2 cm/y	V: dm/yr	Strong movements
Potential debrisflow	M < 0.5 m	M 0.5 – 2 m	M > 2 m
Actual debrisflow	-	H < 1 m	H > 1m
Subsidence	-	Dolines	-

	Estimated Probability in 50 Years	**Estimated Return Period**
High	100 – 82 %	1 to 30 year
Middle	82 – 40 %	30 – 100 Year
Low	40 – 15 %	100 – 300 Year

Fig. 4 Simple scheme for qualitative landslide risk assessment as used by the Swiss Federal Office of Water and Geology (after Lateltin 1997). In this method landslide events are not subdivided according to their probability of occurrence (*E* kinetic energy, *V* landslide velocity, *M* thickness of potential source material, *H* height of debris flow)

possible terrain factors which contribute to landsliding are combined with a landslide inventory map using data-integration techniques (Van Westen 1993; Bonham-Carter 1996; Chung and Fabbri 1999). Chung and Fabbri (1999) developed statistical procedures under the name of predictive modelling, applying favourability functions on individual parameters. Using these statistical methods, terrain units or grid cells can be adjusted to new values representing the degree of probability, certainty, belief or plausibility that the respective terrain units or grid cells may be subject to a particular type of landslide in the future.

One of the aspects that has received attention in the literature is the basic mapping unit used in statistical landslide susceptibility assessment. Automatic classification of terrain units from DEMs is one of the challenging topics (Carrara et al. 1995; Rowbotham and Dudycha 1998; Iwahashi et al. 2001; MacMillan et al. 2004). Chung et al. (1995) defined the concept of unique condition polygons, made by overlaying the input layers, as the basic units for statistical analysis. Möller et al. (2001) defined and described so-called soil mechanical response units (SMRU) which are generated from a DEM using GIS and were used as input parameters in a combined heuristic and soil mechanical approach to landslide hazard assessment for an area in Rheinhessen, Germany. Several publications deal with a combination of fuzzy membership values in GIS-based landslide hazard mapping. Some examples are given by Juang et al. (1992), Davis and Keller (1997), Binaghi et al. (1998), Ercanoglu and Gokceoglu (2001) and Gorsevski et al. (2003).

Bivariate statistical analysis, using weights of evidence modelling, is still widely used as it offers a flexible way of testing the importance of input factors for landslide susceptibility and can be used as a supporting tool in expert-based mapping (e.g., Lee et al. 2002; Suzen and Doyuran 2003; and Van Westen et al. 2003). Multivariate statistical analysis also remains an important and widely used tool (Carrara et al. 1999; Santacana et al. 2003). New tools in statistical landslide hazard assessment appear regularly. Among the most popular new statistical landslide hazard methods reported in the recent literature are logistic regression and artificial neural network (ANN) classifiers (e.g., Chung et al. 1995; Rowbotham and Dudycha 1998; Ohlmacher and Davis 2003; Dai and Lee 2003). An ANN offers a computational mechanism that is able to acquire, represent and compute a map taking data from one multivariate space of information to another, given a set of data representing the relationships (Lu and Rosenbaum 2003). An ANN is developed by the use of a set of associated input and output values. The method is not available within existing GIS systems and has been programmed in systems like MATLAB (Lee et al. 2003).

The use of statistical methods for landslide risk assessment has a number of drawbacks. One of these is the tendency to simplify the factors that condition landslides, by taking only those that can be relatively easily mapped in an area or derived from a DEM. Another problem is related to generalization of the causal factors, assuming that landslides happen under the same combination of conditions throughout the study area and through time, whereas in reality the environmental factors change continuously. The third problem is related to the fact that each landslide type will have its own set of causal factors and should be analysed individually. The statistical models generally ignore the temporal aspects of landslides and are not able to predict the impact of changes in the controlling conditions (e.g., water table fluctuations, land use changes, climatic change). They cannot therefore provide full temporal probability information and are difficult to use in quantitative risk assessments. However, this could be improved if for the generation of the statistical relations, use is made of landslide inventory maps for particular time intervals, or better for events with a particular return period.

There have been recently some publications that demonstrate the usefulness of statistical methods combined with landslide maps from different periods. For example, Zêzere et al. (2004) present a method for a probabilistic analysis at a regional scale for a site north of Lisbon (Portugal). They used logistic regression with unique condition polygons and a landslide dataset partitioned in different sets related to landslide type, time period and part of the area. Prediction-rate curves are used for the quantitative interpretation and classification of the susceptibility map. As landslides are related to triggering rainfall events with a particular return period, they were also linked with temporal probability values. A similar approach was followed for a part of Hong Kong by Dai and Lee (2003). However, both above-mentioned examples resulted in hazard maps and no attempt was made to use them in a risk assessment. Few examples are published on the use of statistical methods in landslide risk assessment. Remondo et al. (2004) recently published an example of such a risk assessment for an area in northern Spain, including the use of past damage data for vulnerability assessment.

Developments in the use of deterministic and dynamic models for landslide risk assessment

In deterministic analysis, the landslide hazard is determined using slope stability models, resulting in the calculation of factors of safety. Deterministic models provide the best quantitative information on landslide hazard which can be used directly in the design of engineering works or in the quantification of risk. However, they require a large amount of detailed input data, derived from laboratory tests and field measurements, and can therefore be applied only over small areas at large scales. When dealing with deterministic slope stability analysis related to shallow rainfall-induced landslides, several authors have developed GIS models coupling a dynamic hydrological model that simulates the pore pressure over time with a slope stability model that quantifies the susceptibility as the critical pore pressure threshold (Dietrich et al. 2001; Terlien et al. 1995; Gritzner et al. 2001; Chen and Lee 2003; Van Beek and Van Asch (2003). The slope stability models developed by the US Forest Survey are also based on the infinite slope equation. Hammond et al. (1992) used this model and introduced the probability of slope failure using Monte Carlo simulations. Other interesting applications showing Monte Carlo simulations combined with uncertainty mapping using fuzzy methods are presented by Davis and Keller (1997) and Zhou et al. (2003).

The deterministic approaches for earthquake-induced landslides hazard analysis are generally based on the simplified Newmark slope stability model, applied on a pixel-by-pixel basis, which can be carried out completely within the current GIS computational environment (Miles and Ho 1999; Luzi et al. 2000; Randall et al. 2000; Jibson et al. 2000). Refice and Capolongo (2002) have implemented a Monte Carlo simulation in combination with the Newmark slope stability model.

Anderson and Howes (1985) used an entirely different approach. They developed a 2-D combined detailed hydrological slope stability model (also for curved failure surfaces) currently available as CHASM, which they apply systematically on a series of profiles along road tracks in order to construct a detailed deterministic hazard map. Van Asch et al. (1993) and Moon and Blackstock (2003) used the same approach in their study on deterministic landslide hazard assessment for a small catchment in Vorarlberg (Western Austria) and in the city of Hamilton in New Zealand, respectively. Miller and Sias (1998) worked with a two-dimensional finite-element model to simulate unconfined aerial groundwater fluxes and to calculate water table elevations and factors of safety for large landslides using Bishop's simplified method of slices along individual slope transects.

In the field of landslide runout modelling also, GIS has been used extensively (Hungr 1995; Chen and Lee 2003). Dymond et al. (1999) developed a GIS-based computer simulation model of shallow landslides and associated sediment delivery to the stream network, for different rainstorm events and land use scenarios. A high-resolution DEM is one of the major components in the model. De Joode and van Steijn (2003) presented a simple but complete process model, simulating initiation of landslips by rain, water runoff and transport of material along the slope, erosion and sediment transport, and the propagation of debris flows in the main gullies. Cellular automata have also been extensively used in modelling the flow velocity and extent of landslides (Avolio et al. 2000).

Dynamic deterministic modelling in a GIS environment has been used by many investigators (Terlien 1996; Montgomery et al. 1998; Dietrich et al. 2001, Van Beek 2002). Given the meteorological input, deterministic models are able to forecast the spatial and temporal frequency of slope failures. Recently developed dynamic models linked to a GIS are able to forecast the propagation of material after failure and to delineate the zone where the elements will suffer a certain impact (Chen and Lee 2003). They therefore deliver the perfect input for vulnerability and risk calculations. Deterministic models are not dependent on the present situation like statistical models. Deterministic models may forecast changes in hazard under different land use scenarios not currently existing and changes in hazard caused by climate change.

However, the limitations in the parameterization of these models leave many uncertainties concerning the absolute frequency values and impacts. At the catchment scale only the triggering of more simple landslides with simple hydrological configurations can be modelled. Owing to limited data about landslide dates and spatial distribution, calibration and validation of the models are difficult. In some cases runout distances and distribution of the thickness of material in the deposition zone are important elements for calibration and for selecting the right rheology in these propagation models (Van Asch et al. 2004).

Relevant new advances in the methods of collection and integration of basic data for landslide risk assessment and challenges for the future

Improved topographic data

With the fast development in geo-information science and earth observation, there are more and more tools available for carrying out a more reliable landslide hazard and risk assessment.

As topography is one of the major factors in landslide hazard and risk analysis (as it is also for other types such as flooding, forest fires, volcanic eruptions, etc.), the generation of a digital representation of the surface elevation, called the Digital Elevation Model (DEM), plays a major role. During the last 15 years or so, there have been important changes both in terms of data availability and in terms of the software that can be used on normal desktop computers without extensive skills in photogrammetry. Photogrammetrical methods using aerial photos, the use of (high-precision) GPS and the digitizing and interpolation of contour maps, have now become standard procedures that can be carried out by most landslide research teams themselves. In addition, almost the entire world is now covered by a DEM with a spatial resolution of 30 m (outside of the US distributed at 90 m) from the NASA Shuttle Radar Topography Mission (SRTM) (Rabus et al. 2003), which serves as a good basis for landslide studies at regional scales. SAR interferometry (InSAR) is gaining increasing importance as a technique for rapid and accurate topographic data collection.

A number of spaceborne InSAR systems are operational (ERS, ENVISAT, RADARSAT). In recent years this technique has been used to monitor and measure landslide movements (Fruneau et al. 1996; Rott et al. 1999; Kimura and Yamaguchi 2000; Rizo and Tesauro 2000; Squarzoni et al. 2003). The applicability of the DInSar method for detecting slope movements in vegetated terrain is much more limited, however, due to phase decorrelation and atmospheric disturbances. Better results can be obtained by carrying out measurements on a subset of image pixels corresponding to point wise stable reflectors (permanent scatterers, PS) and exploiting long temporal series of interferometric data, as demonstrated by Colesanti and Wasowski (2004). Radar interferometry has proved to be a good method for DEM generation and for monitoring slow moving landslides, but is not very effective in landslide inventory mapping.

Another new tool for detailed topographic mapping is laser scanning. LiDAR is an acronym for light detection and ranging and is an airborne method using a pulse laser to measure the distance between the sensor and the surface of the Earth. Normally LiDAR point measurements will render so-called DSMs, which contain information on all objects on the Earth's surface, including buildings, trees, etc. LiDAR data have been used by Montgomery et al. (2000), Dietrich et al. (2001), and Crosta and Agliardi (2002) in the analysis of landslide susceptibility assessments. Norheim et al. (2002) made an extensive comparison of DEMs derived from LiDAR and airborne InSar for the same area and concluded that the accuracy of the LiDAR DEM was far better—comparable in accuracy but more economical as compared with a DEM derived by photogrammetrical techniques from aerial photographs. Terrestrial laser scanning methods have also been developed and successfully used in the characterization of the 3-D structure of landslides or rock slopes (Rowlands et al. 2003). Once the technique for laser scanning has become more economic and areas are covered by high-accuracy DEMs at regular time intervals, it might also be used as a good source for mapping new landslides through change detection.

Improved landslide inventory mapping

As mentioned above, landslide inventory maps are the key component of a landslide risk assessment, especially if they represent landslides with date, type and volume, and if they are updated after major triggering events (Coe et al. 2004b). Although there is an important role for the collection of such data on the ground, where mobile GIS (Wong 2001; Ng et al. 2004) may be a new tool for improved mapping, most of the information has to come from remote sensing. The possibility of using satellite remote sensing data for the identification and mapping of small-scale slope failures has been improved substantially over the last decade. Now there is a potential value for the application of multispectral and panchromatic data with up to 1 m spatial resolution (CEOS 2001).

Two different approaches can be seen in the use of remote sensing data for landslide inventory mapping. Many of the medium resolution systems such as LANDSAT (Honda et al. 2002), SPOT (Yamaguchi et al. 2003) and IRS-1 (Nagarajan et al. 1998) have been used in situations where landslides without vegetation can be differentiated spectrally from the rest of the area. ASTER data is currently one of the least expensive types of medium resolution satellite data available for landslide mapping. ASTER's 14 multi-spectral bands (in the VNIR, SWIR and Thermal IR) and stereo capability facilitate mapping and assessment of landslide hazard on a regional scale and especially in areas where detailed geological and topographic maps are not available (Liu et al. 2004).

The other approach is the use of stereo imagery in the geomorphological interpretation and the mapping of landslides, using high-resolution imagery such as IKONOS or Quickbird (De la Ville et al. 2002; Petley et al. 2002). With the current GIS and image processing software such as ERDAS StereoAnalyst or ILWIS, it is also possible to generate a stereo pair from one orthorectified image and a DEM. This is especially useful in those cases where the original image data is only available monoscopically. Several techniques can be used to visualize the digital stereo images, such as anaglyph, chromadepth, polarized light, or the use of a screen stereoscope mounted on the computer screen.

Improved landslide initiation modelling

In current practice, landslide hazard assessment is often restricted to empirical rainfall threshold methods or multivariate statistical techniques (Caine 1980; Corominas 2000; Fan et al. 2003). These approaches ignore the physical mechanism by which a landslide is initiated by rainfall, considerably limiting the ability to forecast and quantify the hazard. It is impossible with existing approaches to predict the landslide hazard where historical data are not available or are not statistically significant. Historical data are irrelevant and unusable if changes occur in the boundary conditions due to human activity,

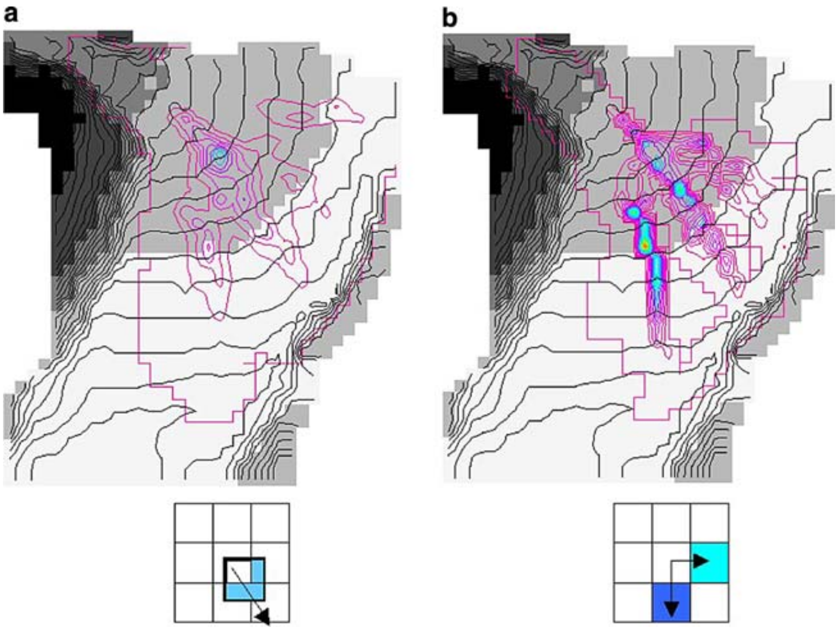


Fig. 5 The distribution of debris flow material on a fan with the same discharge but using different routing algorithms. **a** Material from the central pixel is shifted as a "block" along the direction of slope aspect. The direction and distance of movement of this block determine the distribution in the neighbouring cells. **b** The material is distributed in an *X* and *Y* direction. The local slope in the *X* and *Y* direction determines the amount of material flowing out into the neighbouring cells

land use change, deforestation or climatic change (Van Beek and Van Asch 1999; Van Beek 2002). Quantifying the triggering mechanisms is thus an essential step forward in landslide hazard forecasting. Therefore, a challenge will be to link and properly quantify the physical processes related to the infiltration of rainfall to groundwater recharge and consequently the triggering of slope movements (Savage et al. 2003; Coe et al. 2004a, b). In particular, the role of the unsaturated zone as a link between vegetation and deeper ground water storage for landslides and the role of preferential flows (as in fissures) have to be considered (Van Asch et al. 1996; Bogaard and Van Asch 2002), in order to better forecast changes in failure frequency induced by land use and climate change.

Improved runout modelling

Runout modelling is rather complicated because between initiation and stopping the materials involved suffer various transformations depending on the initial composition, the morphology of the path and the material incorporated during the flow (Savage and Hutter 1991; Rickenmann 2000; Iverson et al. 2004). The behaviour of the deposit and its parameters are often different from the initial material characteristics. As in many cases there is no information on velocities or flow type; the rheological regimes are difficult to estimate. The challenge will be to determine the rheological behaviour of different types of rapid gravity flows based on the morphology, distribution and sedimentological characteristics of the material deposited along the flow path, to qualify the expected mechanism and apply appropriate physically based models to simulate the corresponding flows.

It is also a challenge to model the exact location of the source areas of debris flows and the spreading of material on the deposition fans. Different runout models linked to a GIS can simulate a quasi 3-D distribution of material, but a major problem remains when the topography does not exhibit clearly pre-defined relief components (such as obvious concavities which function as source areas for the debris flows and gullies) where the propagation of material can be routed. In the latter case different algorithms in a GIS for routing of the material may give quite different distribution patterns (see Fig. 5). The spreading of debris on the fan can also be influenced—especially near the apex—by small temporal obstructions not incorporated in the DEM but which contribute to the uncertainty of the hazard zonation. These technical problems can be solved using stochastic techniques delivering a spatial and temporal probability of runout patterns.

Temporal landslide hazard assessment

A challenge will be to add the temporal dimension to the susceptibility maps at the catchment scale in order to produce real hazard maps. The use of deterministic methods in combination with probabilistic statistical techniques may provide one of the solutions. A way has to be found to upscale deterministic site-specific hydro-mechanical models for various types of landslides to the catchment scale, in order to assess the temporal occurrence of these processes and where possible to assess magnitudes in terms of volume, area and/or runout distances.

Methodologies and models for determining the change in spatio-temporal pattern of landslide and avalanche hazard and risk in various climate scenarios are necessary.

Improved landslide vulnerability assessment

One of the main challenges is in the field of landslide vulnerability assessment. Unlike other types of hazards, such as earthquakes, flooding or windstorms, relatively little work has been done on the quantification of the physical vulnerability due to landslides. Decision support systems for loss estimation for these other types of hazards are well developed and range from simple tools (Radius 1999) to complex multi-hazard loss estimation systems, such as HAZUS (FEMA 2004). The problem with landslide vulnerability assessment is that there are many types of landslides, which all should be evaluated separately (see Table 1). Such vulnerability information should come from historical studies in the first place, but can be combined with modelling approaches and empirical approaches (Glade 2004).

Discussion and conclusions

The literature on landslide risk assessment indicates that a lot of developments have taken place in the last decade, and that quantitative risk assessment on a site investigation scale or for the evaluation of linear features (e.g., pipelines, roads) is feasible (Wu et al. 1996; Morgenstern 1997; Einstein 1997; Fell and Hartford 1997; Hardingham et al. 1998; Wong et al. 1997; Lee and Jones 2004). However, the generation of quantitative risk zonation maps, expressing the expected monetary losses as the product of probability (of occurrence of a landslide with a given magnitude), costs (of the elements at risk) and vulnerability (the degree of damage of the elements at risk due to the occurrence of a landslide with a given magnitude) seems still a step too far, especially at medium scales (of 1:10,000–1:50,000). It is also questionable whether there is a need for such type of information at this scale. The main use of medium-scale risk maps is in development planning and emergency response planning (Michael-Leiba et al. 2003). Assessment of the level of risk is sufficient on this scale in order to decide which areas have to be avoided for new developments or to select areas of relative high risk for more detailed (deterministic) investigation to quantify the risk and to provide cost–benefit analyses for future developments. It may not be required for local authorities to know the exact amount of losses expected in monetary values, even more because the level of risk due to landslides is often several orders of magnitude lower than those for other hazards, such as traffic accidents, fires and diseases (Finlay and Fell 1997).

Considering all the difficulties mentioned above, it will be appreciated that a risk assessment at a medium scale only could be a qualitative, or at best a semi-quantitative one. The risk classes, categorized with such terms as "very high", "high", "moderate", "low" and "very low" risk, should be defined on the experience of the expert with support from statistical or deterministic models and depend on the likelihood that a slide will occur and the consequences that such an event would have for the elements at risk. It is recommended that these levels of risk include a description of their practical implications. It is recommended to execute the risk mapping for single types of landslides, as the effect of one type of slope failure is quite different from that of other types. The mapping should be directed towards geomorphological evidences related to aspects that influence the risk, such as runout distances, size and depth of landslides, retrogressive (slope upwards) movements of slides, within a given environmental setting.

Geo-information tools have become essential for landslide hazard, vulnerability and risk assessment. At large scales deterministic models are best used for determining factors of safety, and dynamic models to portray the trajectories of landslides. When combined with probabilistic methods related to the variability of input data and return periods of triggering events, the probability of failure can be obtained. As soil depth is one of the most crucial parameters in deterministic landslide hazard assessment, the use of shallow geophysics should receive more attention, e.g., geo-electrical methods, high-resolution seismic reflection surveys, ground penetrating radar (GPR), electromagnetic (EM) and electrokinetic spontaneous potential (SP) measurements (Bruno and Martillier 2000)

At medium scales the most important input data is event-based landslide inventory maps, which are made directly after any major disaster (earthquake, rainstorm, hurricane, etc.). Such an inventory by geomorphologists should emphasize landslide characteristics (types, volumes) as well as damage caused to the different elements at risk. These landslide data are combined with factor maps (e.g., slope angle, lithology, etc.) using heuristic or statistical methods, to produce landslide susceptibility maps. When combined with landslide frequency analysis, during which landslide information from temporal databases is combined with rainfall and earthquake records, it is also possible to obtain landslide probabilities. Earth observation data should be used on a more routine basis in the regular mapping of new landslide phenomena and the generation of landslide databases.

The mapping of elements at risk for a landslide risk assessment project is not fundamentally different from other types of hazard mapping, although more research should be carried out as to which characteristics of the elements at risk are essential for the landslide vulnerability study. In the original equation of risk, the cost of elements at risk plays an important role, although the cost aspect is hardly ever really taken into account in landslide risk studies. More work also needs to be done on the definition of the vulnerability of elements at risk for landslides and the generation of damage functions. The difficulty in defining landslide vulnerability values is the uncertainty of the expected landslide magnitude or volume.

Finally, the various components of landslide risk assessment should be integrated in risk information/management systems which should be developed as spatial decision support systems for local authorities dealing with risk management.

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